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REPORT ON MEETING TO REVIEW MARAGING STEEL PROJECTS

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2. To supplement established Service activities in providing technical advisory services to producers, melters, and fabricators of the above materials, and to designers and fabricators of military equipment containing these materials.
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Contract No. AF 33(616)-7747
Project No. 2(8-8975)

REPORT ON MEETING TO REVIEW MARAGING STEEL PROJECTS

A. M. Hall*

A Maraging Steel Project Review was arranged by the Load Bearing Materials Section of the Applications Laboratory, Directorate of Materials and Processes, Aeronautical Systems Division. The review was held on November 7 and 8, 1962, at the Biltmore Hotel in Dayton, Ohio, with Lt. W. F. Payne acting as general chairman. This was a sequel to a similar meeting at Wright-Patterson Air Force Base, Ohio, on May 14, 1962.

The purpose of the review was to discuss the technical progress which has been achieved on the low-carbon high-nickel maraging steels. In particular, the objective was to exchange technical information and to evaluate the results forthcoming from pertinent technical investigations, in order to provide a basis for estimating the suitability of the maraging steels in critically important structural applications. To this end, an understanding of the current status of the technology of the maraging steels was sought, with especial emphasis on the advantages of the steels and on the problems that can be expected in using them.

The two-day review was opened by Col. Lee R. Standifer, Director, Materials and Processes, Aeronautical Systems Division. There followed 21 presentations by members of a variety of Government agencies and facilities, industrial concerns, and research organizations. Abstracts of the presentations appear in the Appendix to this memorandum. In the body of the memorandum, the highlights of meeting are summarized and the author's recommendations on the subjects covered at the meeting are presented.

Resumé of the Meeting

The effort represented by the programs in progress on the maraging steels is considerable in size and comprehensive in scope. The purpose of a substantial fraction of the effort is to explore the nature and behavior of these steels and to develop information on properties, notably strength and toughness, and on the factors that influence these properties. Also, considerable effort is being spent in studying the forming, machining, and welding of these steels, and the influence of such fabrication processes on mechanical properties. Much of the work is directed fairly specifically at rocket motor case applications with particular attention to the extra large boosters.

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The bulk of the current effort is on the 18 Ni (250) and 18 Ni (300) steels, with less interest being shown in the 20 Ni, the 25 Ni and the 18 Ni (200) steels.* The 18 Ni (250) and 18 Ni (300) steels are considered to be superior to the 20 Ni and 25 Ni steels in fracture toughness. Also, the 25 Ni steel requires a more complicated heat treatment for strengthening. The 18 Ni (200) steel is too new to have been given great consideration as yet.

From the results reported during November 7 and 8, 1962, the following inferences are drawn regarding the current status of the technology of the maraging steels:

(1) It is clear that 0.2 per cent offset yield strengths up to some 295 ksi and uniaxial ultimate tensile strengths up to about 310 ksi can be obtained in the maraging steels, as annealed and aged. It is possible to add 50 to 60 ksi to these values by cold working the metal about 50 per cent (reduction of area) after annealing and before aging. In addition, the results being obtained in the different evaluational programs suggest that the maraging steels have considerably greater fracture toughness than do other high-strength materials at equivalent strength levels.

(2) It is evident that the mechanical properties obtainable in these steels vary significantly from one grade of maraging steel to another. The 18 Ni (300) steel develops the highest strength and, apparently, the highest fracture toughness. The 18 Ni (250), the 20 Ni and the 25 Ni steels develop somewhat lower strengths than the 18 Ni (300) type. The fracture toughness of the 18 Ni (250) steel seems generally to be somewhat below that of the 18 Ni (300) but substantially above that of the 20 Ni and 25 Ni steels. The latter two steels appear to be fairly similar in fracture toughness. The mechanical properties of the 18 Ni (200) steel have not been probed extensively; the alloy was designed to develop a 0.2 per cent offset yield strength of 200 ksi.

(3) The numerous mechanical-property values reported for each grade of maraging steel show strong composition sensitivity. This is a common experience with precipitation-hardening alloys. Variations in titanium and molybdenum contents, as well as in cobalt content, produce marked variations in response to heat treatment, i.e., in the mechanical properties obtainable. In a number of instances, especially with the 18 Ni (300) steel, the strength properties, which one might have expected from the steel's designation, were not actually achieved in the material.

*The abbreviated alloy designations refer to the following compositions:

Designation	Composition, weight per cent					
	Ni	Ti	Al	Co	Mo	Cb
18 Ni (200)	17-19	0.15-0.25	0.05-0.15	8-9	3.0-3.5	-
18 Ni (250)	17-19	0.3-0.5	0.05-0.15	7-8.5	4.6-5.1	-
18 Ni (300)	18-19	0.5-0.7	0.05-0.15	8.5-9.5	4.7-5.2	-
20 Ni	18-20	1.3-1.6	0.15-0.35	-	-	0.3-0.5
25 Ni	25-26	1.3-1.6	0.15-0.35	-	-	0.3-0.5

(4) The heat treatment of the maraging steels is quite straightforward. The 25 Ni steel behaves much like a precipitation-hardenable semi-austenitic stainless steel. On cooling, at any cooling rate, after being annealed at a temperature such as 1500 F, the steel is austenitic. "Trigger annealing" in the range of 1100 to 1300 F is thought to cause eta phase and perhaps Fe_2Ti to precipitate, thus raising the M_s temperature so that the steel can be completely transformed to martensite on subsequent cooling and holding at -100 F. High strength is then obtained by aging in the vicinity of 900 F.

Heat treatment to strengthen the 18 Ni* and 20 Ni grades is much simpler and to an extent parallels that of the martensitic precipitation-hardenable stainless steels. The 18 Ni and 20 Ni steels are but slightly sensitive to cooling rate so that, regardless of the cooling procedure, they are essentially martensitic at room temperature, after being annealed at a temperature in the range of 1500 F. They are then brought to high strength by aging in the vicinity of 900 F.

Because they combine higher strength, greater fracture toughness and simpler heat treatment, the 18 Ni (250) and 18 Ni (300) steels are currently being given preference over the other grades of maraging steel.

(5) For the heat sizes thus far handled and the forms thus far made, the maraging steels present no serious melting and working problems. Welding is another matter. The existence of regions in weld-heat-affected zones which are impaired with respect to aging response, so that they do not develop the expected strength properties on post weld aging, is a cause for concern.

(6) The results of burst tests of a number of subscale vessels of different designs tend to confirm the previously mentioned indications that both the 18 Ni (250) and 18 Ni (300) steels themselves, as well as welded and aged joints of these steels, have a high degree of fracture toughness. Some low burst strength values have been obtained; perhaps a number of these can be attributed to the region of impaired aging response in the weld-heat-affected zones.

RECOMMENDATIONS

The following suggestions are offered on the basis of the presentations made at the meeting on November 7 and 8, 1962:

- (1) An improved understanding of the basic processes which go on in the strengthening of the maraging steels should be developed. A better understanding will greatly assist producers in controlling the quality and properties of mill products, and fabricators in forming and heat treating the alloys to produce reliable components and assemblies.

*When reference is made to the 18 Ni steels, all three grades are implied, i.e., the 18 Ni (300), 18 Ni (250) and 18 Ni (200) steels.

- (2) The sensitivity of the mechanical properties of these steels to variations in composition should be thoroughly investigated. Improved ideas should be obtained of the typical and minimum properties to be expected. A good understanding should be acquired of the extent to which "off chemistries" can be compensated by adjustments in heat treating schedules. It is probable that the precipitation-hardening process offers less latitude in this respect than does the conventional quench-and-temper hardening of steel.
- (3) A concerted effort should be made to place the concepts of fracture toughness and the methods of studying and reporting it on a more uniform basis. For example, it would appear useful to report fracture toughness as the net fracture strength obtained in the presence of the largest stress-raising defect which is beyond the inspection system's capability to detect. This is a meaningful quantitative value which could be used directly in design calculations, and the basic data to calculate it must generally be obtained anyway when materials are evaluated by the current parametric methods. Thus, this value could be reported along with the parametric value.
- (4) The significance of regions of impaired aging response in weld-heat-affected zones should be determined. If it is established that they are important, then an intense effort should be made to find ways to eliminate or minimize the problem.

To assist in evaluating the importance of these regions of weld-heat-affected zones, a larger number of burst tests of subscale vessels should be made, and the fractures should be studied thoroughly, particularly to establish point of origin. In this connection, greater use should be made of vessel designs containing longitudinal seam welds, so that the ability of welded joints to resist bursting pressure will be put to a good test.

- (5) The ductility and reduction of area results obtained on round-bar tension tests show that the maraging steels display an unusually high degree of plastic instability. Hand-in-hand with this feature is their notably low capacity to work harden.

These characteristics raise questions about the ability of the maraging steels (a) to sustain dynamic loading without low energy failure and (b) to adjust to high localized stress. In this connection, the relatively poor fatigue properties of the maraging steels may be considered as symptomatic. In

addition, the tendency of vessels to shatter into myriad pieces when burst tested, in a manner expected of brittle materials, may reflect these peculiarities of the maraging steels.

The significance of the plastic instability of these steels should be studied. The possibility that this characteristic could lead to catastrophic failures, if it is not well understood, should not be overlooked.

- (6) In examining the maraging steels, quite understandably attention is being focused largely on rocket motor case applications. However, there may well be other critically important applications in which these steels may be extremely well suited. They should retain their mechanical properties for long time periods at temperatures up to within 200 degrees of the aging temperature. Also, they seem to be distinctly superior to other ultrastrong steels in resistance to stress-corrosion cracking.

Along this line, it is believed that more consideration should be given to the 18 Ni (200) steel and to the development of other modifications of the maraging steels possessing modest strength, i.e., 150 to 200 ksi yield strength. It is conceivable that such steels would have desirable combinations of strength, toughness, and capabilities for field assembly into reliable structures.

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INTRODUCTION

by

Col. Lee R. Standifer, Director, Materials and Processes,
Aeronautical Systems Division

Col. Standifer pointed out the need for considerably more technical information on the maraging steels before intelligent decisions can be made regarding their suitability in a number of applications important to the Air Force. It was his opinion that these steels could ultimately become tonnage items. However, before their potential can be attained, an understanding of the basic physical metallurgy on which they depend and, particularly, the mechanisms by which they are strengthened, is required; reliable information on toughness, especially in heavy sections, is needed; the technology of welding these steels must be developed, with emphasis on the need for post-weld heat treatment and the strength and toughness of weld-heat-affected zones. Col. Standifer indicated the need for caution and thoroughness in preceeding with these new steels and expressed the hope that the information presented in the review would cast light on the important unanswered questions relating to the low-carbon high-nickel maraging steels.

SESSION I - EVALUATION AND FABRICATION OF MARAGING STEEL

by Staff of the Curtiss-Wright Corporation

1. Air Force Contract Work Program

by E. Gilewicz

The program encompassed evaluation of one vacuum-arc remelted heat each of the 18 Ni (250), 18 Ni (300), 20 Ni and 25 Ni steels, together with the fabrication and testing of subsize pressure vessels and the fabrication and testing of full size 40-inch-diameter second-stage Pershing-type cases. Allegheny-Ludlum supplied 5000-lb heats in the form of sheet and bar stock. The criteria used to evaluate the steels themselves were strength, fracture toughness, welding quality, and the strength and toughness of welded joints.

For each steel, the effect of solution annealing conditions, cold working, warm working, and aging conditions was studied. Tensile specimens were 8 inches by 1-1/2 inches with a 2-inch by 1/2-inch reduced section; the fracture toughness specimens were 8 inches by 1-1/2 inches and were center notched with fatigue cracks at each end of the notches. The gage was 0.115 inch.

For the 18 Ni (250) steel, the optimum heat treatment seemed to be a solution anneal at 1500 F plus aging 3 hours at 900 F which gave a K_C of 251* in the longitudinal direction and a K_C of 231 in the transverse direction. Peak yield strength (0.2 per cent offset) of 263.5 ksi was obtained by aging 10 hours at 900 F. Cold reductions from 20 to 70 per cent were studied. Peak yield strength of 320 ksi was achieved by cold rolling 50 per cent and aging 10 hours at 850 F. Cold working reduced fracture toughness. With cold reductions of 50% followed by aging at 850 F, K_C was 170 in the longitudinal direction and 90 in the transverse direction. Warm working was done at 1200, 1400, and 1600 F with the highest yield strength obtained by working at 1400 F followed by aging 10 hours at 850 F (265 ksi yield strength).

The 18 Ni (300) steel behaved in much the same way. Annealing at 1500 F plus aging 10 hours at 900 F gave a top yield strength of 296.5 ksi. The K_C in the transverse direction was 220 for a 1-hour age at 900 F, 182 for 3 hours and 140 for 10 hours at this temperature. Again, aging after 50 per cent cold reduction gave optimum strength, 345 ksi yield strength after 10 hours at 900 F and 338 ksi after 10 hours at 850 F. Fracture toughness was reduced by cold working. Material cold worked 40 per cent and aged had K_C of 75 in the transverse direction. However, aged material worked more than 50 per cent beforehand showed improved fracture toughness (possibly due to reversion of martensite to austenite). The best yield strength in warm worked and aged material was obtained in metal worked at 1400 F (270-300 ksi yield strength). No data were obtained for 1500 F finishing temperature.

Elevated-temperature tests were made on the 18 Ni (300) type using round bars. With the standard aging treatment, the yield strength was 223 ksi at 250 F and 200 ksi at 750 F. The strength dropped rapidly at temperatures above 750 F.

In the 20 Ni steel, yield strength after aging rose steadily with annealing temperature for temperatures from 1400 to 1600 F. The K_C values dropped correspondingly. The highest K_C values were 185 for the longitudinal direction and 150 for the transverse direction, obtained on aging after annealing at 1400 F. Aging 3 hours at 900 F after 30 per cent cold reduction gave peak strength (305 ksi yield strength). The K_C values for cold worked and aged material were markedly lower than for annealed and aged material, though the decline in K_C after 20 per cent cold reduction was gradual. Again, 1400 F seemed to be the optimum warm working temperature. The general heat treatment selected as optimum was one hour at 1450 F plus 10 hours at 900 F.

For the 25 Ni steel, the general heat-treating conditions considered optimum were an anneal at 1450 F for 1/2 hour followed by a "trigger" anneal (ausage) of 4 hours at 1200 F, plus immediate refrigeration at -115 F for 16 hours, and finally aging 3 hours at 900 F. However, annealing temperatures of 1400 to 1700 F were tried. Better K_C values were 180 (longitudinal) and 125 (transverse). The effect of 20 to 50 per cent cold reduction was studied; the yield strength of cold worked and aged material increased slowly with the degree of reduction. The cold worked specimens were not ausaged or refrigerated. However, in all cases, annealed and aged metal was stronger than cold worked and aged material. Elevated temperature properties for the 25 Ni alloy with the standard heat treatment were 250 ksi yield strength at 250 F and 200 ksi yield strength at 750 F.

* K_C units are ksi $\sqrt{\text{in.}}$; K_C of 150 ksi $\sqrt{\text{in.}}$ is considered a marginal value.

Plots of K_C vs yield strength indicated that, at any given yield strength, the K_C values for the 20 Ni and the 25 Ni steels were substantially lower than those for the 18 Ni (250) and the 18 Ni (300) steels. The last named had the highest values. This order of merit prevailed for both annealed and aged as well as cold worked and aged material.

2. Weldability of 18, 20, and 25 Per Cent
Nickel Maraging Steel Sheet
 by W. Fragetta

This program was directed toward developing procedures for welding 18 Ni (250), 18 Ni (300), 20 Ni and 25 Ni steel sheet with the TIG process and evaluating the strength and reliability of the joints. Annealed sheet, 0.070 and 0.140-inch thick, and 0.140-inch thick sheet cold rolled 50 per cent, were used. The filler wires included an 18 Ni (250) and an 18 Ni (300) composition, a 20 Ni wire and a cast steel containing 16 per cent nickel, 10 per cent cobalt, 1.5 per cent copper, 5 per cent molybdenum, 0.4 per cent titanium and 0.02 per cent carbon. No preheat nor postheat was used.

The weld deposits tended to be mixtures of martensite and austenite, as deposited. The martensite surrounded islands and stringers of austenite. Distinct weld-heat-affected zones were always observed. There was noticeable grain growth in the heat affected zones.

Horizontal hardness transverses showed noticeable variations in the hardness of the weld-heat-affected zones. As-welded material showed rises in the hardness curves at distances somewhat remote from the fusion line. The regions represented were undoubtedly age hardened during welding. In the case of the 25 Ni steel, a hardness drop occurred in the parent metal region near the fusion line which probably reflected a substantial reversion to austenite. On aging after welding, these various effects were quite well effaced and hardness values (about 50 R_C) equivalent to those achieved in the corresponding unaffected parent metal were obtained. However, there was a very narrow band in the heat affected zone where there was a 1 to 2 point R_C reduction in hardness. This is probably the zone that was heated to 1200 to 1300 F.

Taken together, the results indicated best weldability by the 18 Ni (250) steel; 100 per cent joint efficiency was achievable with high yield strength and fracture toughness after aging; and sound welds were obtainable in 0.070 and 0.140-inch thick material. With the cast filler wire and a post weld aging treatment of 3 hours at 900 F, yield strengths of 266 to 268 ksi were obtained. The 18 Ni (300) steel was next, with joint efficiencies of 91 to 95 per cent; the best yield strength was obtained with the cast filler metal. Joint efficiencies of 100 per cent were obtained in the 20 Ni steel with good K_C values comparable to the unwelded sheet metal. However, this steel showed considerable sensitivity to section size. The 25 Ni steel did not fare very well, exhibiting poor joint efficiencies, although the corresponding K_C values were comparatively good. Brittle tensile failures occurred in the weld-heat-affected zones of 0.070 and 0.140-inch thick material from this alloy. The general conclusion was that weldments in the 18 Ni (250) steel behaved in a manner similar to that of the base metal regarding response to heat treatment.

Tensile test data were supplemented by bend test data for the 0.140 and 0.070-inch stock. Bends of 2T radius were made satisfactorily for those conditions in which high efficiency welds were produced. K_c specimens were 2 x 8 inches with center slots and wing-type fatigue cracks. The cracks were produced by bending fatigue before aging. Ink staining was used to determine slow crack growth.

3. Fabrication of 18 Per Cent Nickel Rocket Motor Cases by J. Zack

One 40-inch-diameter case of the second stage Pershing type was fabricated and another is in progress. The speaker stated that the objective was to demonstrate the increased reliability of the 18 per cent nickel steel over D6AC which is now being used for production cases.

The same tooling was used as for D6AC. The alloy, 18 Ni (300) steel, was found to be satisfactorily machinable at hardnesses of 32 to 36 Rockwell-C. The surface finishes were equivalent to those obtained on D6AC. Spun ring forgings 24 inches long were used for the cylindrical section. These were reduced 55 per cent in two passes, then annealed, and reduced in three more passes to the desired thickness. The metal is said to spin successfully, forward spinning being more satisfactory than backward spinning. There was a tendency for the diameter to grow but this was compensated for by increasing the feed. Welding was done in two passes with the TIG process using matching filler wire in the second pass. One case was welded, machined, and aged, while the second was welded, aged, and then machined. The idea behind the contrasting procedures was to check on dimensional stability and machining problems.

The first case, the one thus far completed, was expanded 0.04 to 0.05 inch after welding to compensate for distortion and weld mismatch. On subsequent aging, the forward dome went out of round and the I.D. shrank. Also, the thrust termination ports shrank one to five mils.

It was concluded that the distortion which occurs on aging can be handled by fixturing; also, critical parts should be machined after aging. It was further concluded that the material was more stable dimensionally than D6AC, simpler to heat treat, and more corrosion resistant. Finally, it was observed that the maraging steel could be machined in the aged condition at a hardness of Rockwell C-52.

4. Hydrostatic Testing of Subscale and Full Scale Units by R. Johnson

Some eight subscale pressure vessels 6 and 14 inches in diameter were fabricated and tested. The 18 Ni (300) steel was used. With two exceptions, the bottles were essentially composed of a spun cylindrical section

with elliptical end closures welded on; it is understood that the assembly was fully heat treated after fabrication. Two bottles contained girth welds at the mid section. The procedure used to test these subscale bottles was to cycle three times to half the expected burst pressure and then go on to burst the vessels. Time from proportional limit to burst was about 2 minutes, and total pressurizing time was about 5 minutes. A light spindle oil was used for pressurizing.

The burst stresses attained in the tests of the subscale vessels were generally in the range of 330 to 350 ksi. Average biaxial improvement was in the order of 16 per cent for the proportional limit, 16.7 per cent for the 0.2 per cent offset yield strength and 16.5 per cent for the ultimate tensile strength. Typically, bursting produced numerous fractures, though all were reported to be shear-type failures.

The burst stresses for the vessels containing central girth welds were comparatively low, being 303 and 310 ksi, respectively. There was some speculation that the vessels were somewhat thinner at the welds than in the body of the material and that this circumstance might account for the poorer performance of these two bottles.

The full scale case (0.072-inch-thick 40-inch-diameter 20-inch-long cylindrical section) which had been welded, machined, and aged was pressurized three times but not taken up to burst. The maximum pressure induced a hoop stress of 240 ksi. During pressurizing, it was thought that the proportional limit had been reached at this stress level. Later examination of the data indicated that the proportional limit had not been reached. The burst stress was estimated as about 320 ksi including a biaxial gain of about 15 per cent. Prior pressure tests had provided information from which the burst stress could be predicted from the proportional limit stress. In pressurizing subscale and full-scale vessels of D6AC steel, excellent correlation was obtained in data for the various size vessels. The von Mises criterion apparently is accurate through the proportional limit and probably the yield strength, but is less accurate where there is substantial plastic deformation, as at burst strength.

SESSION II - MECHANICAL PROPERTIES OF MARAGING STEELS

5. Preliminary Evaluation of Mechanical Strength and Fracture Toughness of Thick Plate Maraging Steel by W. J. Persin, Mellon Institute

The objective of the program at Mellon was to investigate the strength and toughness of the 18 Ni steels in the form of unwelded and welded plate, rings and forgings, as well as to study the deep drawing and hot spinning of these steels. Plate from 3/8 to 3/4 inch thick was used. Fracture toughness was studied using a 6-inch-wide specimen, center notched with fatigue cracks at the ends of the notch. The 18 Ni (250) specimens were 0.375 inch thick and the 18 Ni (300) specimens were 0.350 inch thick.

For the 18 Ni (300) steel, in the form of fully heat treated 0.350-inch-thick plate, a G_c value of 1650 in. lb/sq in. was obtained with specimens containing a 40 per cent crack. The speaker considered that the 18 Ni steels displayed the greatest toughness of any of the ultrahigh-strength steels. Notched and unnotched round specimens were also tested.

Some V-notch Charpy values determined at room temperature for welded 1/2-inch-thick plate, subsequently aged to the 250 ksi yield strength level, were reported. The filler wire was of matching composition. When the weld was parallel to the rolling direction, values of 11 ft-lb for the parent metal, 13 ft-lb for the weld-heat-affected zone, and 19 ft-lb for the weld, were obtained. With the weld transverse to the rolling direction, the corresponding values were 22, 21, and 21 ft lbs.

A joint efficiency of 95 per cent was obtained in 18 Ni (200) steel, annealed 1 hour at 1500 F and aged 3 hours at 900 F.

Small vessels, 3-1/2 inches O.D. with 1/8-inch wall have been made by deep drawing and hot spinning. The plan is to put fatigue cracks in these vessels and then pressurize to the calculated 0.2 per cent offset yield strength. If the vessels will tolerate this stress without failure, they will then be subjected to low cycle fatigue. The schedule will be to stress to the 0.2 per cent offset yield strength, hold 2 minutes, release, and repeat to failure.

6. Welding and Machining of Plate Material and Forgings by W. D. Abbott, Excelco Developments, Incorporated

The program described has for its purpose the development of welding and machining information on plate and on forged bar stock. It is intended that the information accumulated be useful in the preparation of specifications covering welding and machining. Plate 3/8 inch to 1 inch thick and bar stock 1-1/2 inches in diameter were used and represented 9 heats of the 18 Ni type.

The TIG process was used, the joints being fully restrained. No cracks were noted and porosity occurred only when the titanium content of the filler wire was below 0.40 per cent.

High joint efficiencies were obtained. For 18 Ni (250) steel plate welded with wire of matching composition, efficiencies of 95 to 100 per cent were obtained when the material was post weld aged at 925 or 950 F. When aged at 1000 F, the joint efficiency was 92 per cent.

A few preliminary experiments were made in which the joint was locally aged after welding. The results were very promising and the speaker stated that plans are underway to repeat the work under more carefully controlled conditions. Such experiments are extremely important to the construction of large cases which cannot be completely heat treated after assembly.

A study was made of dimensional change accompanying aging and shrinkage during welding. The latter effect was similar to weld shrinkage in low alloy steels. Investigations were made of tapping and milling and double aging. Tapping could be carried out at hardnesses of Rockwell-C 51. Speeds for single point cutting should be similar to those used for ultrahigh-strength low-alloy steels. The hardness of stock which failed to respond completely during aging at 900 F was improved by a second aging at 925 F.

7. Investigation of the Properties and Fabricability
of 3/4-inch-Thick Air-Melted 18Ni-7Co-5Mo Plate
 by F. D. Duffey, Newport News Shipbuilding and Dry
 Dock Company, and B. V. Whiteson and Z. P. Saperstein,
 Douglas Aircraft Company

This program, which is being carried out jointly by Douglas and Newport News, is directed toward evaluating the 18 Ni (250) steel for application in large motor cases. Studies are being made of formability, machinability, heat treatment, fracture toughness, and welding. The material is 3/4-inch plate.

The results to date indicate that hot-rolled plate should be annealed before use. This heat treatment reduces the directionality which is displayed in the mechanical properties of the hot rolled metal. A series of aging treatments was used on this material to determine aging response.

The findings also indicate that plate behaves in a manner similar to that of sheet with respect to fracture toughness. In this connection, the 18 Ni (250) steel showed a greater tolerance for partial cracks than did AISI 4340 at the same strength level.

The 18 Ni (250) steel was readily formed and machined in the annealed condition, responding in a manner equivalent to that of annealed AISI 4340. However, high springback was observed in forming 5-foot-diameter cylinders.

In welding 3/4-inch plate of the 18 Ni (250) alloy, no preheat nor postheat was required. Post weld aging produced high strength. It was found, however, that the filler wire should have a titanium content high

enough to compensate for the loss which occurs in welding so that sufficient titanium will be present in the weld to insure full response to aging. High silicon and manganese fostered porosity and cracks in the weld. Submerged-arc-welded joints showed a yield strength of 228 ksi with 5 per cent elongation after a post weld aging treatment of 3 hours at 900 F. When joints were annealed at 1500 F for one hour and then aged 3 hours at 900 F a yield strength of 234 ksi was achieved with an elongation of 6 per cent.

Definite weld-heat-affected zones were observed in metallographic sections. A region of the zones was found which did not respond well to aging. This region seemed to correspond to that part of the parent metal which had been heated to about 1100 or 1200 F during welding. The response of the region was restored by full annealing. It was speculated that reversion to stable austenite was responsible for the behavior of this region. A thermal-gradient specimen was used in studying the effect of heating in the heat-affected zone on hardness and microstructure.

Work is in progress on filler wire composition, on fluxes, on post weld aging treatments, on notched tensile tests of welded specimens, on the metallography of weldments, on the feasibility of repair welding, on effect of environment and on pressure testing of vessels.

8. Comments on Several Army Research Programs on Maraging Steels by W. Carman, Frankford Arsenal

A program on the fracture toughness of cold rolled and aged 25 Ni steel strip will use grain oriented and conventional material. The former will come from directionally solidified ingots. All material is to be processed in the same manner and evaluated with 4-inch by 12-inch center notched specimens.

A program is in progress also to form a monolithic Pershing second stage case with no welds in critical areas. It is proposed to make this component from a forged pancake blank by hot cupping, cold drawing, nosing and contour machining. The schedule will include appropriate process anneals, heat treatment, final machining, and inspection. The materials of ultimate interest are the 20 Ni and the 18 Ni (300) steels.

Other work concerns slow crack growth in the 18 Ni (250) and 18 Ni (300) steels under low-cycle fatigue conditions.

9. Variations in Physical and Mechanical Properties by Dr. E. Kula, Watertown Arsenal

A moderate effort on the maraging steels is under way at Watertown Arsenal. The effect of heat treating variables on strength and toughness is being studied. It was pointed out that of the 6 heats thus far examined only one could be heat treated to the strength level claimed by the producer, and its toughness was poor. It was suggested that closer control of chemistry was needed. Properties at cryogenic temperatures are being studied. The

directionality and anisotropy of these steels are being examined. Charpy tests have been made using standard specimens and specimens with fatigue cracks in the notches. Standard Charpy specimens of 18 Ni (250) fractured with 23 ft-lb energy at room temperature. Some ballistic work is in progress; these steels seem satisfactory as armor from the standpoint of piercing but are unacceptable from the viewpoint of fragmentation. Their tendency to fragment seems related to a propensity toward laminating (banding).

9a. Evaluation of High-Strength Lightweight Laminated Pressure Vessels of Lap Joint Construction

by R. E. Stegler, Republic Aviation Corporation

At Republic Aviation, a program is in progress on the design and manufacture of bonded rocket motor cases. The cylindrical section comprises an inner and an outer hoop section bonded together with an adhesive to make the case. In this program, the 18 Ni (300) steel is being studied.

The hoops are constructed from sheet by rolling and welding using the TIG process without filler wire. The gages being investigated are 0.025, 0.040, and 0.064 inch. In welding, minimum heat input is favored in order to avoid overaging and other undesirable effects in the weld-heat-affected zones. The aim is to achieve 85 per cent joint efficiency in welded and aged joints. Efficiencies of 94 to 97 per cent were achieved. The procedure desired is to weld a preform and round up by stretching. With the maraging steel it was found that 4 per cent is the maximum stretch the alloy can take, so they stop at 3.8 per cent.

Wide variations have been noted in the elastic modulus which are believed related to some aspects of the material's history. The variations were most noticeable in annealed material and seemed to be sensitive to age. Aging appeared to reduce or eliminate the variations.

10. Properties of Maraging Steel Press Forgings

by R. B. Sparks, Wyman-Gordon Company

A progress report was made on an experimental closed-die press forging program encompassing (1) making several full-size (40-inch-diameter) Pershing rocket motor case closures from the 18 Ni (300) steel in connection with the Curtiss-Wright program discussed above, (2) making a 55-inch-long airframe structural part from the 18 Ni (250) steel both air melted and vacuum-arc remelted, and (3) making small cylindrical shapes from the 18 Ni (300) and the 25 Ni alloys.

The steel for the closures was obtained from Latrobe. One of the forged end closures was cut up for evaluation of properties. The finished forgings were reported to be fairly homogeneous with respect to the tensile properties obtained after aging. The ratio of notched to unnotched strength was 1.3 at a 0.2 per cent offset yield strength of 275 ksi and a K_t factor of 11. The aim of the forging schedule was to finish at 1500 to 1700 F.

In making the airframe structural part, it was noted that the air melted stock showed a little less ductility in the short transverse direction than did the vacuum-arc remelted material.

It was observed that the heats of metal were banded. Charpy impact properties on the aged material were 9.5 to 14 ft lb at room temperature.

Further work is being done to determine effects of amount of working and the effects of microstructure (particularly banding) on the properties.

SESSION III - MECHANICAL PROPERTIES AND FABRICATION
OF MARAGING STEELS

11. Fracture Toughness Studies on Nickel

Maraging Steels

by H. L. Smith, Naval Research Laboratory
and Dr. H. Romine, Naval Weapons Laboratory

Emphasis was placed on the importance of fracture toughness and fracture analysis in evaluating structural materials for critical applications. In this connection, the high-nickel low-carbon maraging steels look attractive. For rocket motor cases, the requirement is adequate fracture toughness at such a yield strength as is needed to meet a minimum yield strength-to-density ratio of approximately 1×10^6 . For steel (density: 0.282 lb per cu in) the required yield strength is about 282 ksi, for Ti-6Al-4V (density: 0.156 lb per cu in) the yield strength needed is 156 ksi and for glass fiber reinforced plastic it is 70 ksi (density: 0.07 lb per cu in). The results of work done thus far has shown that the 18 Ni and 20 Ni steels can meet the requirement, the yield strength which these steels must attain being 290 ksi. The 25 Ni steel did not fill the bill. The strength of these steels was not sensitive to section size up to 0.16-inch thickness (the heaviest gage used in the program). The work reported was done on material 0.04, 0.08 and 0.16 inch thick as cold rolled 50 per cent and aged 3 hours at 900 F as well as on the 18 Ni steel in these thicknesses as annealed one hour at 1500 F and aged 3 hours at 900 F.

The fracture toughness specimen used was 3 inches wide with a fatigue-cracked center slot. No difference in results was obtained whether the fatiguing was done before or after aging.

The results indicated that, for the 18 Ni steel cold worked 50 per cent and aged, K_C increased from about 110 for 0.04-inch-thick material to about 230 for material 0.16 inch thick. The K_C values for the 20 Ni and 25 Ni steel, 50 per cent cold worked and aged, were not greatly affected by section thickness; they were generally low at all thicknesses, i.e., in the range of 100. As annealed and aged, the 18 Ni steel gave K_C values of 150 and above. These results taken together were considered to indicate that 18 Ni steel has the toughness required for a rocket motor case sheet material.

Results of stress-corrosion tests were reported. The 18 Ni steel showed less loss in load carrying ability from stress corrosion than did 300 M. For example, there was a 5 per cent loss in ocean water for the 18 Ni steel at 285 ksi yield strength, and a 20 per cent loss in tap water for 300 M at 235 ksi yield strength.

Additional work on the 18 Ni steel showed a loss in fracture toughness as strain rate was increased and as temperature was decreased.

12. Partial Thickness Fatigue Crack Tensile Test and
Center Fatigue Crack Tensile Test of 18Ni-9Co-5Mo-0.8Ti
3/8-Inch Plate

by G. R. Sippel, Allison Division of General Motor Corporation

It was pointed out that, because premature failures in rocket motor cases can usually be traced to small defects, it is important to know the tolerance of a material for small flaws in order to fully evaluate the material for such an application. The usual length of a failure-nucleating defect is near the limit of inspection, i.e., 0.050 to 0.150 inch in length.

Partial-thickness fatigued cracks, 0.050 to 0.200 inch, and through-fatigued cracks, 0.400 to 0.600 inch, in length were used. The materials studied were 3/8-inch-thick 18 Ni (300) steel plate with a tensile strength of 301 ksi, a vacuum-consumable electrode melted 24-inch-diameter D6 forging with a 215 ksi yield strength, and vacuum consumable electrode melted forgings of Ti-6Al-4V at tensile strengths of 165 and 180 ksi. The 18 Ni steel had been annealed 1 hour at 1500 F and aged 3 hours at 900 F. The fracture strength specimens were 2 inches by 8 inches with a 1-inch by 2-inch reduced section. The materials were studied in thicknesses of 0.100 and 0.200 inch.

All the materials were relatively insensitive to partial cracks of lengths less than 0.100 inch, the D6 being but little affected by crack lengths up to 0.200 inch. On the basis of gross and notch strength, the 18 Ni steel was superior to the other two materials at partial crack lengths up to 0.200 inch. If density is taken into account, by using the gross strength-to-density ratio, then the titanium alloy and the high nickel steel were equivalent at crack lengths up to about 0.150-inch length. Over 0.200-inch length, all three materials were competitive.

13. Mechanical Property Tests and Certain
Aspects of Weldability

by G. E. Grotke, Westinghouse Electric Corporation

Welding studies on the 18 per cent nickel, 250,000 psi yield strength grade, were reported. The objective was to confirm the reported performance of the new steel and to investigate certain aspects of weldability, such as restraint-cracking, which have, to the present, received little attention.

Data were presented on the tensile and V-notch Charpy impact performance of welded joints made by both the argon-shielded MIG welding process and the cold-wire-fed TIG welding process. The latter was done in an argon-filled, dry-box to evaluate the possible enhancement in toughness obtained with minimized atmospheric contamination. The results suggested that reannealing after welding is unnecessary, simple local re-aging giving quite high strength. The strength values cited for joints were in the order of 235 ksi yield strength which is equivalent to 90 per cent joint efficiency; the V-notch Charpy values were about the same as those of the base metal, i.e., 12-17 ft-lbs.

Two regions in the heat-affected zone were found with impaired response to aging. One had been heated in the range of 1100 to 1400 F and the other to 2400 to 2500 F. To gain more information in these regions, the resistance heating microstructure-simulation technique was employed to determine the effect of peak temperature thermal cycles in the range 1100 - 1400 F and 2400 - 2500 F. The hardness, strength, and toughness of the various structures, after a 900 F aging treatment, were discussed. It was concluded that, under the welding conditions used, the impairment at 1100 to 1400 F was not significant, while that at 2400 to 2500 F was. Yield strength values obtained were 275 ksi for the unaffected parent metal, 270 ksi for metal heated to 1300 F, and 240 ksi for metal heated to 2500 F.

Since the presently envisioned large-size motor cases will require materials in relatively heavy thicknesses, it is required that the weld zones of rigid connections provide minimum crack sensitivity under conditions of appreciable restraint. The propensity to restraint-cracking was evaluated by means of conventional Controlled Thermal Severity (CTS) specimens in the plate-thickness range 1/2 to 1 inch, manually welded with experimental-composition covered electrodes. The results were very encouraging. Only one small weld-heat-affected zone crack occurred in 15 specimens. Heat input limitations were recommended for welds in the 18 Ni (250) steel.

14. Spinning, Welding, and Machining of Grade 250 Marage Steel

by L. E. Hersher, Borg-Warner Corporation

The 18 Ni (250) steel was reported to spin well and to machine satisfactorily with carbide tipped tools. Subscale cases 13-1/2 inches in diameter and 100 inches long with 0.090 inch wall were fabricated. The material was welded with 18 Ni (300) filler wire. The cases were hydrotested.

15. TIG Shielded Arc Welding of 0.080 and 0.125-Inch Maraging Steel Sheet

by Dr. C. Adams, Massachusetts Institute of Technology

The mechanical properties observed in welded joints of the 18 Ni (250) and the 18 Ni (300) steels were discussed. Joints were made in 0.080, 0.125, and 0.5-inch-thick material by the TIG and the short arc processes. Post weld aging was carried out at 900 F for 3 hours. The performance of joints under biaxial loading was measured by means of a slotted tensile specimen described in an article entitled "Biaxial Strength of Welds in Heat Treated Steel Sheet", by D. A. Corrigan, R. E. Travis, V. P. Ardito and C. M. Adams, Jr., which appeared in the Research Supplement of the March, 1962, issue of the Welding Journal on pages 123S to 128S. Joint efficiencies well over 90 per cent were obtained, the short arc method giving the higher efficiencies for plate and TIG giving the higher efficiencies for sheet. The 18 Ni (300) steel showed a biaxial gain in the order of 15 per cent, while the 18 Ni (250) steel showed a biaxial gain of 9 per cent.

A number of 8-inch-diameter pressure vessels were also made and burst tested. The material used was consumable electrode remelted 18 Ni (300) steel in the form of 0.080-inch-thick sheet. The cylindrical section was fabricated by the roll-and-weld method. The heads were hydrospun. The procedure was to roll, weld, anneal one hour at 1500 F, weld on heads, and age 3 hours at 900 F. The filler wire used in welding was the 18 Ni (250) type steel. It was reported that when the short arc was used a hoop stress at burst of 243 ksi was obtained, but when TIG was used a hoop stress of only 165 ksi was achieved. The failures generally seemed to start in the longitudinal seam weld and then run along the edge of the weld. The starting point for the failure of one vessel was at the junction of a girth weld and a seam weld.

16. Evaluation of 18 Ni (300)

Forging Steel Forgings

by F. C. Nordquist, General Dynamics, Fort Worth

The objective was to determine whether the 18 Ni (300) steel would be a satisfactory material for forged high-strength aircraft components. Four fairly complex closed-die forgings were made. One was forged at 2300 F, the others in the range of about 1800 to 1640 F. The steel was more difficult to forge than AISI 4340.

Optimum smooth-bar and notched tensile results were obtained on forged and annealed stock aged 3 hours at 900 F. The stress-concentration factor was 6.3. The stock had been worked at the more moderate forging temperatures. This same stock was somewhat weaker and markedly less ductile in the short transverse direction than in the other major directions. The overheated forging (forged at 2300 F) suffered loss of strength and ductility.

Tension-tension fatigue studies were made of forged, annealed and aged material. The 10^7 endurance limit in the short transverse direction was about 95 ksi and about 115 ksi in the longitudinal direction. The presence of a notch with a K_t of only two dropped these values to about 60 ksi and 65 ksi, respectively. The smooth bar fatigue behavior of the over-heated forging in the longitudinal direction approximated that of the normal forgings in the short transverse directions. The notched-bar tests of the overheated forging, whether longitudinal or short transverse, gave results about the same as those for the normal forgings in the short transverse direction. The corresponding fatigue properties of a correspondingly forged AISI 4340 steel, heat treated to the same tensile strength level, were considerably better than the fatigue properties of the 18 Ni (300) steel.

Results were reported which showed a great deal more resistance to stress corrosion cracking in a saline environment by the 18 Ni (300) steel than by AISI 4340, both steels being heat treated to the same strength level and subjected to the same stress.

**17. Metallurgical Investigation of Maraging Steels For
Missile Motor Cases**

by T. H. Burns, Thiokol Chemical Corporation, Alpha Division

The investigation reported on covered a study of the forming, welding, heat treating, and notch toughness of the 18 Ni (250) and 18 Ni (300) steels. The influence of strain rate was examined on the basis that fracture toughness data at strain rates comparable to those occurring on ignition of a rocket are needed. For most conventional fuels, this was estimated as 0.05 in/in/sec which was reported to correspond to achievement of peak pressure in 150 milliseconds. The results of experimentation indicated that the G_c values of the materials tested were not notably influenced by strain rate within the range of 0.0005 to 0.15 in/in/sec. At the strain rates prevailing in a pre-cracked Charpy V-notch test, the fracture toughness shown by D6AC, AISI 4340, and the 18 Ni (250) steel was quite high, while that of the 18 Ni (300) steel was comparatively low. It was noted also that, at section thicknesses above about 0.15 or 0.20 inch, fracture toughness was influenced by section thicknesses, decreasing with increasing thickness.

A few cold-drawn 2-inch-diameter cups were machined and girth welded to form miniature pressure vessels 10 or 15 inches long, the thickness being 0.047 inch. Some cups were split longitudinally to provide vessels with longitudinal seam welds. One vessel of 18 Ni (300) steel welded with 18 Ni (250) wire and aged at 900 F for 3 hours gave a burst strength of 346 ksi. Another bottle made of 18 Ni (300) steel cold rolled 40 per cent and welded with 18 Ni (300) wire and aged burst at a stress of 373 ksi. A vessel in which 18 Ni (300) and 18 Ni (250) steels were mixed had a burst stress of about 370 ksi. It was of interest to note that this vessel did not burst at at weld.

Comments were made on the character of the weld-heat-affected zone. A region of impaired response to aging was observed, but it was not believed to have affected burst test results. The speaker did not feel that the weld-heat-affected zone is a matter to be overly concerned about in thin sections. However, it was speculated that the situation might be quite different in heavy sections. Minimum heat input in welding was advised.

Banding was noted in all 15 heats studied and was identified as a phenomenon to be studied.

SESSION IV - MARAGING STEELS IN ROCKET MOTOR CASES

18. Data on the Effect of Loading Rate

by J. Srawley, Naval Research Laboratory

Data developed by J. M. Krafft of NRL indicate an inverse relationship between the log of compressive yield strength and the log of loading time. The material under test was the 18 Ni (300) steel cold worked 50 per cent. For a loading time of 100 seconds the compressive yield was 290 ksi, rising to 330 as loading time decreased to 0.001 second. The reverse was the case for K_{IC} which varied from 165 at 100 seconds to 130 at 0.001 second.

19. Maraging Steels

by R. Decker, The International Nickel Company

The subjects discussed included the character of the weld-heat-affected zone, the influence of trace elements, banding, hydrogen embrittlement, stress corrosion cracking, the elastic modulus and comments on two new maraging steels.

Study of impairment of regions in the weld-heat-affected zone to aging response indicated few problems elsewhere than the region heated to about 1200 F. The extent of impairment would seem to depend on the dwell time at 1200 F which, in turn, is a function of heat input.

The harmful effect of sulfur on Charpy V-notch values was reiterated.

Banding was considered to be a problem originating in ingot segregation. Titanium was found to segregate, and molybdenum to a lesser extent. High annealing temperature (i.e., 2200 to 2300 F) were considered to reduce or eliminate banding. The presence of inhomogeneously distributed non-metallics, like sulfides and carbides, was believed responsible for differences between longitudinal and transverse mechanical properties. The following etchant is reported to have been used to reveal structural features: 50 ml HCL, 25 ml HNO_3 , 1 g $CuCl_2$ and 150 ml H_2O .

As to hydrogen embrittlement, the data reported suggested resistance to delayed failure. However, hydrogen caused flaking in one commercial heat.

Stress-corrosion cracking tests are in progress in the high-sulfur, high-chloride atmosphere of Bayonne, New Jersey, and in the marine atmosphere of Kure Beach, N. C., as well as in aerated artificial sea water. Three-point-loaded specimens and U-bend specimens were used. A few U-bend specimens have failed at Kure Beach after 35-45 days. Only one failure has occurred thus far at Bayonne; it was a U-bend specimen of 18 Ni (300) steel.

Scatter in modulus was not confirmed. The value for aged material was given as 27×10^6 . The value for annealed material was somewhat less.

A cast steel was discussed which contains 16-17 Ni, 10 Co, 4.8 Mo, and 0.4 Ti. It attains 230 ksi yield strength at room temperature. In addition, a high-temperature alloy was mentioned which contains 15 Ni, 9 Co, 5 Mo, 0.7 Ti, and 0.7 Al. It is reported to possess improved mechanical properties and structural stability to 1000 F.

20. High Performance Rocket Motor Cases

by R. C. Dethloff, The Budd Company

The 20 Ni and 25 Ni steels were investigated in the form of sheet and strip for suitability in the Budd Company's helical case design. These steels were among a number of materials with strength-to-density ratios of 1×10^6 and more, which were being evaluated.

The mechanical properties of the 25 Ni steel were found to be lower than those of the 20 Ni steel and the heat treatment more complicated. Therefore, more effort was placed on the latter steel. Three different heats of this steel were studied. From the results obtained with the first heat, the composition of the other two heats was changed to raise the Ti from 1.3 to 1.7 and the Al from 0.2 to 0.5 and the Si was dropped from 0.15 to 0.01; in addition, boron and zirconium were added. The objective was to achieve 300 ksi yield strength in sheet and strip stock.

The second heat was evaluated in the form of annealed 0.125 and 0.075-inch thick strip, as well as in the form of 0.032 and 0.075-inch strip cold rolled 65 per cent. A yield strength as high as 380 ksi was attained with limited ductility. Weldability was evaluated with the TIG process using filler wires of various compositions. This work was followed by studies of response to post weld aging.

A 20-inch-diameter chamber was fabricated employing a single thickness of 0.040-inch-thick by 12-inch-wide strip assembled by a helical butt weld. The chamber was 40 inches long and enclosed with elliptical heads processed from 0.060-inch sheet. The steel used was from the third heat which was intended to duplicate the second heat in composition.

Tests after assembly showed that the strength of the helical welds was low and erratic; the other welds and the parent metal were satisfactory. Another chamber aged at the unusually low temperature of 425 F had seemingly satisfactory strength properties but the joint efficiency was only 56 per cent. The burst failure of this vessel seemed to have started in surface pits in the strip; the welds were not involved. Efforts to duplicate the condition of the first vessel were unsuccessful and the cause of its poor performance remains unknown. For obvious reasons, this is a disturbing situation. Nonetheless, The Budd Company feels that the maraging steels will become useful materials and will be successfully applied at strength levels to 300 ksi.

21. Evaluation of High Nickel Steel for Application
in Large Boosters

by W. S. Tenner and R. E. Anderson, Aerojet-General Corporation

The program under discussion had for its objectives (1) determination of the effect of melting, rolling and forging practice on mechanical properties, (2) evaluation of the materials in terms of fracture toughness and notch sensitivity to establish useable strength levels, (3) evaluate weldability and develop welding techniques to produce reliable welds from the standpoint of strength and toughness, and (4) prepare the process specifications required to fabricate large boosters from the high-nickel steels.

The steels being investigated are the 18 Ni (200) as air melted and as vacuum degassed, the 18 Ni (250) as air melted, as vacuum degassed and as vacuum-arc remelted, and the 18 Ni (300) steel as vacuum-arc remelted. The forms are 1/2-inch and 3/4-inch-thick plate and some forged shapes.

It has been found that high-quality charge materials are needed, that finishing with Ca to fix S is desirable, that vacuum degassing is notably beneficial and may make vacuum-arc remelting unnecessary, and that good hot working practice is to soak at 2300 F and work at 1950 to 1500 F. The steels were reported to be readily weldable and responsive to heat treatment and tougher than other materials at comparable strength levels and under equivalent conditions.

Further work is in progress to select the optimum steel, to obtain more fracture toughness data, and to further evaluate welding procedures.

LIST OF DMIC MEMORANDA ISSUED
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Copies of the technical memoranda listed below may be obtained from DMIC at no cost by Government agencies and by Government contractors, subcontractors, and their suppliers. Others may obtain copies from the Office of Technical Services, Department of Commerce, Washington 25, D. C.

A list of DMIC Memoranda 1-117 may be obtained from DMIC, or see previously issued memoranda.

DMIC Memorandum Number	Title
118	Review of Recent Developments in the Metallurgy of High-Strength Steels, July 21, 1961, (AD 259986 \$0.50)
119	The Emittance of Iron, Nickel, Cobalt and Their Alloys, July 25, 1961, (AD 261336 \$2.25)
120	Review of Recent Developments on Oxidation-Resistant Coatings for Refractory Metals, July 31, 1961, (AD 261293 \$0.50)
121	Fabricating and Machining Practices for the All-Beta Titanium Alloy, August 3, 1961, (AD 262496 \$0.50)
122	Review of Recent Developments in the Technology of Nickel-Base and Cobalt-Base Alloys, August 4, 1961, (AD 261292 \$0.50)
123	Review of Recent Developments in the Technology of Beryllium, August 18, 1961, (AD 262497 \$0.50)
124	Investigation of Delayed-Cracking Phenomenon in Hydrogenated Unalloyed Titanium, August 30, 1961, (AD 263164 \$0.50)
125	Review of Recent Developments in Metals Joining, September 1, 1961, (AD 262905 \$0.50)
126	A Review of Recent Developments in Titanium and Titanium Alloy Technology, September 15, 1961, (AD 263167 \$0.50)
127	Review of Recent Developments in the Technology of Tungsten, September 22, 1961, (AD 263888 \$0.50)
128	Review of Recent Developments in the Evaluation of Special Metal Properties, September 27, 1961, (AD 263994 \$0.50)
129	Review of Recent Developments in the Technology of Molybdenum and Molybdenum-Base Alloys, October 6, 1961, (AD 264291 \$0.50)
130	Review of Recent Developments in the Technology of Columbium and Tantalum, October 10, 1961, (AD 264983 \$0.50)
131	Review of Recent Developments in the Technology of High-Strength Stainless Steels, October 13, 1961, (AD 264984 \$0.50)
132	Review of Recent Developments in the Metallurgy of High-Strength Steels, October 20, 1961, (AD 265135 \$0.50)
133	Titanium in Aerospace Applications, October 24, 1961, (AD 266927 \$1.50)
134	Machining of Superalloys and Refractory Metals, October 27, 1961, (AD 268081 \$1.00)
135	Review of Recent Developments in the Technology of Nickel-Base and Cobalt-Base Alloys, October 31, 1961, (AD 266004 \$0.50)
136	Fabrication of Tungsten for Solid-Propellant Rocket Nozzles, November 2, 1961, (AD 268311 \$0.75)
137	Review of Recent Developments on Oxidation-Resistant Coatings for Refractory Metals, November 8, 1961, (AD 266469 \$0.50)
138	Review of Recent Developments in the Technology of Beryllium, November 16, 1961, (AD 267079 \$0.50)
139	Review of Recent Developments in the Technology of Tungsten, November 24, 1961, (AD 268082 \$0.50)

LIST OF DMIC MEMORANDA ISSUED
(Continued)

DMIC Memorandum Number	Title
140	Review of Recent Developments in Metals Joining, December 6, 1961, (AD 268312 \$0.50)
141	The Emittance of Chromium, Columbium, Molybdenum, Tantalum, and Tungsten, December 10, 1961, (AD 269784 \$1.25)
142	Effects of Moderately High Strain Rates on the Tensile Properties of Metals, December 18, 1961, (AD 270167 \$1.00)
143	Notes on the Forging of Refractory Metals, December 21, 1961, (AD 271030 \$1.50)
144	Review of Recent Developments in Titanium Alloy Technology, December 29, 1961, (AD 269209 \$0.50)
145	The Use of Nickel-Base Alloys in the Rotating Parts of Gas Turbines for Aerospace Applications, January 11, 1962, (AD 271174 \$0.75)
146	Magnesium-Lithium Alloys - A Review of Current Developments, February 6, 1962, (AD 272683 \$0.75)
147	An Evaluation of Materials for Rocket-Motor Cases Based on Minimum-Weight Concepts, March 8, 1962, (AD 273297 \$1.00)
148	The Emittance of Ceramics and Graphites, March 28, 1962, (AD 274148 \$2.50)
149	Methods of Strengthening the Ultrahigh-Strength Steels, April 2, 1962, (AD 275041 \$1.00)
150	Compilation of Tensile Properties of High-Strength Alloys, April 23, 1962, (AD 275263 \$1.25)
151	Compatibility of Propellants 113 and 114B2 with Aerospace Structural Materials, April 27, 1962, (AD 275427 \$0.50)
152	Electron-Beam Welding of Tungsten, May 21, 1962, (AD 276283 \$0.50)
153	Brazing and Bonding of Columbium, Molybdenum, Tantalum, Tungsten and Graphite, June 11, 1962
154	The Effects of Decarburization on the Properties of Ultrahigh-Strength Steels, June 18, 1962
155	The Effects of Solutes on the Ductile-to-Brittle Transition in Refractory Metals, June 28, 1962
156	Properties of Mar-Aging Steels, July 2, 1962
157	A Compilation of the Tensile Properties of Tungsten, September 11, 1962
158	Summary of Briefings on Refractory Metal Fasteners, October 8, 1962
159	Nondestructive Testing of Solid-Propellant Rocket Motors, October 24, 1962
160	Identification of Microconstituents in Superalloys, November 15, 1962
161	Electron Microscopic Fractography, December 21, 1962